

- 1 -

SILICON-CONTAINING TITANIUM DIOXIDE, METHOD FOR PREPARING  
THE SAME AND CATALYTIC COMPOSITIONS THEREOF

Field of the Invention

The present invention relates to titanium dioxide. More particularly, the invention relates to a novel modified titanium dioxide, a method for its preparation, a catalyst comprising said novel titanium dioxide and various uses thereof.

Background of the invention

Titanium dioxide,  $TiO_2$ , an important compound having a wide range of utilities, in particular as a catalyst, is generally produced by drying or calcining titanium hydroxide,  $Ti(OH)_4$  (also referred in the art as titanyl hydroxide). Titanium hydroxide itself may be prepared by several methods, using different types of titanium compounds.

Three crystalline forms of titanium dioxide are known in the art: Anatase, Rutile and Brookite. The first crystalline forms, Anatase, is considered favorable for the purpose of catalytic applications (US Patent No. 4,388,288 and US Pat. No. 4,422,958).

The effectiveness of catalytic activity of titanium dioxide, like many other catalysts, is associated with its porous structure. Catalysts having well developed mesoporous and macroporous structure permit not only a high rate of chemical reaction, but also a high rate of diffusion of the reagents into the granules of catalysts, as well as a high

- 2 -

rate of diffusion of the reaction products out of the granules of catalyst.

Many catalytic processes using titanium dioxide are carried out at elevated temperatures. Under severe conditions, the porous structure of the catalyst may partially collapse, thereby causing a significant reduction of the active surface area, which results in decreasing the catalytic activity of titanium dioxide. A partial transformation of the favorable crystalline form, Anatase, into the less favorable form, Rutile, may be observed during such processes. Quantitatively, the thermal stability of the catalyst may be measured by the change in the specific surface area of a sample subjected to calcination (see, for example, French patent application No. 2,621,577 and European Patent Application No. 0311,515).

Since titanium dioxide is a relatively expensive material, it is most desirable that such a catalyst would possess a prolonged effective period of use. The art has addressed the technical problem of improving the thermal stability of titanium dioxide, in order to allow this catalyst to maintain, as much as possible, its porous structure also under severe conditions. The art has particularly attempted to improve the thermal stability of titanium dioxide by combining it with various additives. Useful agents for this purpose may be selected from the group of aluminum, sodium, potassium, calcium or other chlorides, nitrates and powdery silica.

The art has particularly focused in combining titanium dioxide with silicon dioxide, by means of co-precipitation

- 3 -

of titanium hydroxide and hydrous silica (silica gel) from an aqueous solution.

Journal of Catalysis 105, p. 511-520 (1987) discloses the co-precipitation of mixed titanium-silicon hydroxide from a solution containing a mixture  $\text{TiCl}_4$  and  $\text{SiCl}_4$ . The resulting product is described as a support for nickel catalyst.

Precipitation of titanyl sulfate in the presence of a powdery dry silica (SYLOID- -74) was carried out in order to prepare samples containing 20%, 40% and 80% by weight  $\text{TiO}_2$  and investigations with these precipitates as catalyst for selective catalytic reduction of nitrogen oxides, were described in Applied Catalysis A, General 139, 1996 .. pages 175-187.

Journal of Catalysis, 153, p.165-176 (1995) discloses another method involving the co-precipitation of the mixed titanium-silicon dioxide, using the alkoxide sol-gel method and organic compounds of titanium and silicon as the starting materials, (tetra-isopropoxy-titanium and tetra-methoxysilicon correspondingly). The alkoxide sol-gel method is responsible for the formation of mixed titania-silica aerogels. These porous particles were also tested in the reaction of epoxidation of olefins (Journal of Catalysis 153, 177-189, 1995),

Crystalline titanium silicates having specific adsorption and catalytic properties, prepared by the co-precipitation method, were also described in Advances in Catalysis, Vol. 41, 253-327, 1996.

- 4 -

Another approach, attempted by the art to modify titanium dioxide via the combination with silica, is described in Applied Catalysis A, General 139, p. 175-187 (1996). According to this publication, titanium hydroxide is precipitated from an aqueous solution in the presence of powdery dry silica (SYLOID -74). The resulting particles exhibit selective catalytic properties for the reduction of nitrogen oxides (NOx).

The review given above emphasizes that there is a growing need to provide a modified titanium dioxide having improved thermal stability.

It is an object of the present invention to provide a method for preparing improved titanium dioxide, which results in the formation of a novel product having enhanced thermal stability and a well developed mesoporous and macroporous structure.

It is an object of the present invention to provide such a method involving the introduction of relatively small amounts of silicon into titanium dioxide structure.

#### Summary of the invention

The inventors have found an efficient method for producing silicon-containing titanium dioxide with improved thermal stability. The method is based on a reaction of either titanium hydroxide or titanium dioxide with particles of an aqueous silica sol (a colloidal solution of silica). The silicon-containing titanium hydroxide obtained is subjected to a heat treatment, resulting in formation of an improved titanium dioxide possessing enhanced thermal stability. This method is radically different from the methods accepted in

- 5 -

the art involving co-precipitation of mixed titanium and silicon hydroxides.

The inventors have also surprisingly found that the preferred starting material, for the above mentioned treatment with silica sol, is a precipitate of titanium hydroxide which is obtained from an aqueous solution containing inorganic salts of titanium, following a gradual adjustment of the pH in said solution. This method of precipitation yields titanium dioxide having improved structural features, such as high surface area and a well-developed mesoporous structure. When this precipitate is reacting with silica sol, as explained above, a thermally stable titanium dioxide, having a high surface and developed mesoporous structure, is obtained.

Thus, in one aspect, the present invention is directed to a method for preparing thermally stable, silicon-containing titanium dioxide, said method comprising the reaction of titanium hydroxide or titanium dioxide with a silica sol, under conditions which prevent the coagulation of silica particles in said sol, to obtain silicon-containing titanium hydroxide or silicon-containing titanium dioxide, and in the case of silicon-containing titanium hydroxide, heat treating the same to obtain silicon-containing titanium dioxide.

According to the present invention, titanium hydroxide or titanium dioxide prepared by various methods known in the art may be used as the starting material, generally in the form of a wet cake, an aqueous suspension, a dough or in a dried form. According to a preferred embodiment of the present invention, the starting material is a precipitate of

- 6 -

titanium hydroxide, obtained by a precipitation method that comprises the following steps:

- a) providing an acidic aqueous solution containing inorganic salts of titanium and, if required, increasing the pH of the solution to a value above 0.02 but below the value at which precipitation of titanium hydroxide occurs, by introducing into said solution a first alkaline agent;
- b) dissolving in said solution a precursor of an alkaline agent, and causing said precursor to generate said second alkaline agent and thereby to precipitate titanium hydroxide in the solution; and
- c) separating and washing said precipitate of titanium hydroxide.

The solution according to step a) comprises inorganic salts of titanium which are preferably sulfate salts. The concentration of titanium in said solution, calculated in terms of  $\text{TiO}_2$ , is in the range between 20 to 250 g/l.

Preferably, the first alkaline agent optionally used in step a) is selected from the group consisting of ammonia, hydroxides and/or carbonates of alkali metals or alkaline earth metals.

According to a particularly preferred embodiment of the present invention, a precursor of alkaline agent used in step b) is urea, which, upon heating, is decomposed to generate ammonia. The ammonia produced increases the pH of the solution thereby driving the precipitation of titanium hydroxide.

- 7 -

The separation of the precipitate according to step c) is accomplished by acceptable liquid/solid separation techniques, for example by filtration. Preferably, following the separation, the precipitate is washed, and used as the starting material in the preparation of a thermally stable, silicon-containing titanium dioxide.

The inventors have found that the novel method of precipitation described above, which constitutes another aspect of the present invention, is important in determining the catalytic properties of the final titanium dioxide. More specifically, this precipitation method imparts the final titanium dioxide a high surface area and a well developed mesoporous structure. These properties are of great importance in the field of catalysts, involving titanium dioxide use. The precipitate of titanium hydroxide, obtained by the method of precipitation described above, may be converted, if desired, into titanium dioxide without a reaction with the silica sol. Due to its structural properties, the resulting silicon-free titanium dioxide is an effective catalyst which can be used in low-temperature catalyzed reactions.

The silica sol used according to the present invention is a colloidal solution containing silica particles, the diameter of said particles being usually in the range of between 1 and 100nm. The concentration of the silica sol is between 1 and 40%, and preferably between 3 and 20% (w/w), calculated as  $\text{SiO}_2$ . Preferably, a basic silica sol, stabilized with cations such as  $\text{Na}^+$ ,  $\text{K}^+$  or  $\text{NH}_4^+$  is used.

- 8 -

Preferably the titanium hydroxide or titanium dioxide starting material is treated with an alkaline agent, before its reaction with the silica sol, to adjust the pH of said starting material to a value above 6.0, and preferably between 8 to 10. The reaction between the titanium hydroxide or titanium dioxide and the silica sol is accomplished most effectively under alkaline conditions, wherein the coagulation of the silica particles is prevented and the stability of the sol is maintained. The process is carried out at a temperature between room temperature and the boiling point of the liquid phase of the sol, preferably within the range of 70 to 100°C.

Another aspect of the present invention is directed to a thermally stable titanium dioxide containing not more than 18% silicon, calculated in terms of  $\text{SiO}_2$  on dry basis. The said titanium dioxide is a single phase, having essentially the same composition at different points, as determined by the EDAX method. By the term "single phase" is meant a substance consisting of one homogeneous phase, namely, no separate phases of  $\text{TiO}_2$  and  $\text{SiO}_2$  are observed in said substance.

Another aspect of the present invention is directed to a catalyst, comprising:

- a) at least 3% w/w of a thermally stable titanium dioxide containing not more than 18% silicon calculated as  $\text{SiO}_2$ .
- b) A filler, preferably a silica filler; and, optionally
- c) a binder.



- 9 -

Preferably, the silica filler present in the catalyst is selected from the group of natural silica, namely, diatomaceous earth, optionally treated with an acid to remove impurities therefrom, precipitated silica or silica hydrogels, preferably free of any sodium or potassium contamination.

The binder is optional according to the present invention, and is preferably selected from the group of colloidal solutions of silica or hydrogels of silicic acid.

#### In the Drawings:

Figure 1 is the X-ray diffraction diagram of a novel titanium dioxide prepared according to the present invention and calcined at 950°C for 1 hour (example 18)

Figure 2 is the X-ray diffraction diagram of a commercially available titanium dioxide UNITi 908 calcined at 950°C for 1 hour.

Figure 3 is the X-ray diffraction diagram of a novel titanium dioxide prepared according to the present invention and calcined at 950°C for 1 hour (example 23).

#### Detailed description of the invention

The present invention provides a method method for preparing thermally stable, silicon-containing titanium dioxide, said method comprising the reaction of titanium hydroxide or titanium dioxide with a silica sol, under conditions which prevent the coagulation of silica particles in said sol, to obtain silicon-containing titanium hydroxide or silicon-containing titanium dioxide, and in the case of silicon-containing titanium hydroxide, heat treating the same to obtain silicon-containing titanium dioxide.

- 10 -

As explained above, the preferred starting material according to the present invention is a precipitate of titanium hydroxide, obtained by the following method:

a) providing an acidic aqueous solution containing inorganic salts of titanium and, if required, adjusting the pH of the solution to a value above 0.02 but below the value at which precipitation of titanium hydroxide occurs, by introducing into said solution a first alkaline agent;

b) dissolving in said solution a precursor of an alkaline agent, and causing said precursor to generate said second alkaline agent and thereby to precipitate titanium hydroxide in the solution; and

c) separating and washing said precipitate of titanium hydroxide.

In the following description, the preferred embodiments of said precipitation method will be detailed.

The solution according to step a) comprises inorganic salts of titanium, which are preferably sulfate or chloride salts, most preferably sulfate salts. Examples of particularly suitable solutions are solutions of ammonium titanyl sulfate  $(\text{NH}_4)_2\text{TiO}(\text{SO}_4)_2$ , which is a commercially available compound, or solutions containing titanyl sulfate and sulfuric acid. These solutions of titanyl sulfate and sulfuric acid are either commercially available (UNITi 992<sup>TM</sup> produced by KEMIRA) or may be prepared by dissolving available titanium hydroxides or titanium dioxides (UNITi 908<sup>TM</sup>, FINNTiS-230<sup>TM</sup>) in a concentrated solution of sulfuric acid (70% w/w).

- 11 -

The concentration of titanium sulfate,, in the solution used according to step a) of the precipitation method, calculated in terms of  $\text{TiO}_2$ , is in the range of between 10 and 250 g/l and preferably between 40 and 150 g/l.

The pH of a solution containing titanyl sulfate and sulfuric acid is very low. The pH of the solution is adjusted to a value in the range between 0.02 and the value causing the precipitation of titanium hydroxide by introducing into said solution a first alkaline agent which is selected from the group consisting of ammonia, hydroxides and carbonates of alkali metals or alkaline earth metals. Most preferably, the pH of the solution is adjusted in step b) to a value in the range between 0.8 to 1.7 using ammonia as the alkaline agent. When the starting solution is a solution containing  $(\text{NH}_4)_2\text{TiO}(\text{SO}_4)_2$ , the pH is already within the required range and usually no adjustment will be required.

A key feature of the method of precipitation, as provided by the present invention, is that the pH adjustment is carried out in a controlled manner. Initially the pH of the solution is increased to a value somewhat below the pH at which precipitation occurs. This may be achieved by using a first alkaline agent. The precipitation is then accomplished by introducing into the solution a precursor of a second alkaline agent. The first and the second alkaline agents may be the same or different. Following homogeneous dispersion of said precursor, the precursor is allowed to generate the second alkaline agent, which actually drives the precipitation of titanium hydroxide. According to a particularly preferred embodiment of the present invention, the second alkaline agent precursor is urea, which, upon heating, is decomposed to generate the second alkaline agent

- 12 -

itself, i.e. ammonia. The ammonia thus produced increases the pH of the solution, thereby driving the precipitation of titanium hydroxide.

The weight ratio between the quantity of urea, added to the solution according to step b) of the precipitation method, and the quantity of titanium present in the solution (in terms of titanium dioxide) is preferably in the range of between 0.3 to 11.0, more preferably in the range 2-4. Subsequent to the dissolution of the urea, the solution is heated to an elevated temperature, preferably in the range between 90 to 105°C, although other temperatures may also be applicable, whereby ammonia is produced. Most of the titanium hydroxide precipitates quite rapidly, i.e., in several minutes, but preferably, the solution is maintained at said elevated temperature for an additional period of time, to allow a complete precipitation of said titanium hydroxide and concurrently to remove residues of sulfuric acid, which accompany the precipitate. The exact duration of step b) depends on the titanium salt content of the solution, the pH of the solution before the addition of urea, the amount of urea added and the temperature employed. Typically, the duration of step b) is between 1.5-4.0 hours. The value of the pH at the end of this step is above 6.0, usually in the range between 6.2-6.8. The precipitate is separated from the liquid phase, by acceptable methods such as filtration, decantation and centrifugation, and is subsequently washed, preferably by demineralized water.

The precipitate of titanium hydroxide obtained by the precipitation method described above is considered as the preferred starting material for producing silicon-containing titanium dioxide, having enhanced thermal stability,

- 13 -

according to the present invention. Other titanium hydroxide or titanium dioxide preparations, obtained by a variety of methods known in the art, may be also used as the starting material. For example, titanium hydroxide wet cake precipitated according to the procedure disclosed in EP 722905 A1 (after the washing but without the addition of potassium hydroxide and phosphoric acid to) and titanium hydroxide or titanium dioxide prepared according to US 4,929,586 (before the vanadyl oxalate addition). Additional applicable starting materials are the produced by KEMIRA: UNITi 902<sup>TM</sup>, FINNTi S-140<sup>TM</sup> and FINNTi-150<sup>TM</sup>.

The reaction between the titanium hydroxide or titanium dioxide starting material and the silica sol should be accomplished preferably under conditions ensuring the stability of the sol, namely, conditions preventing the coagulation of the silica particles. For this reason, titanium hydroxide or titanium dioxide starting materials, typically in the form of an aqueous suspension, a wet cake, dough or a dry material, is mixed with an alkaline agent before it is contacted with the silica sol. The alkaline agent is preferably selected from the group of an aqueous solution of ammonia, urea, sodium hydroxide or potassium hydroxide. The pH of the resulting mixture comprising the titanium hydroxide or titanium dioxide starting materials and the alkaline agent should be between 6 to 11, and preferably between 8 to 10. Subsequently, the silica sol is introduced into said mixture, maintaining its stability under said alkaline conditions.

The silica sol used according to the present invention is a colloidal solution containing silica particles. It is known that the inner part of said particles consists essentially

- 14 -

of dehydroxylated silica, while silicon atoms located on the outer surface of the particles are hydroxylated. Generally, said silica sols contain cations to neutralize the negative charge of the silica particles. The preferred cations are sodium, potassium and ammonium, the latter being most preferred. Methods of preparation of silica sol, for example, those employing a cation exchange method, are well known in the art.

The concentration of the silica sol used according to the present invention is between 1 and 40%, and preferably between 3 and 20% (w/w), calculated as  $\text{SiO}_2$ . The quantity of the silica sol contacting with titanium hydroxide or titanium dioxide starting material is such that the weight ratio between silicon and titanium, in terms of their dioxides, is preferably in the range of between 0.01 and 0.3, more preferably in the range of between 0.03 and 0.15. It has been surprisingly found that when said ratio is less than 0.1, substantially all the quantity of silica present in the solution is consumed by the titanium hydroxide or titanium dioxide starting material. The inventors believe that some Ti - O - Si chemical bonds are formed resulting in a reinforcement of the structure of the final titania.

The titanium hydroxide or titanium dioxide is contacted with the silica sol at a temperature in the range between ambient temperature and the boiling point of the liquid phase, preferably in the range 70-100°C. The rate of interaction between the silica sol and the hydroxylated surface of titanium hydroxide or titanium dioxide is temperature dependent, said rate of interaction increasing with the elevation of the temperature.

- 15 -

Another aspect of the present invention is directed to a thermally stable titanium dioxide containing not more than 18% silicon, calculated in terms of  $\text{SiO}_2$  on dry basis. The said titanium dioxide is a single phase, having essentially the same composition at different points, as determined by the EDAX method.

Preferably, the surface area of the silicon-containing titanium oxide is greater than  $300 \text{ m}^2/\text{g}$ , and its specific pore volume is of at least  $0.30 \text{ cc/g}$  for pores having a diameter less than  $100 \text{ nm}$ . The silicon-containing titanium dioxide according to the present invention is thermally stable, as apparent from the following tests:

- i) following calcination at  $800^\circ\text{C}$  for 3 hours, it is capable of retaining a surface area above  $28 \text{ m}^2/\text{g}$ , preferably above  $50 \text{ m}^2/\text{g}$ , wherein the silicon content, calculated as  $\text{SiO}_2$ , is 2%, or above  $90 \text{ m}^2/\text{g}$ , preferably above  $200 \text{ m}^2/\text{g}$ , wherein the silicon content, calculated as  $\text{SiO}_2$ , is 18%;
- ii) following a hydrothermal treatment at  $400^\circ\text{C}$  for 5 hours with a mixture containing 90% by volume water vapor and 10% air, it is capable of retaining a surface area above  $120 \text{ m}^2/\text{g}$ , preferably above  $250 \text{ m}^2/\text{g}$ , wherein the silicon content, calculated as  $\text{SiO}_2$ , is 18%.

The present invention also provides a catalyst, comprising:

- a) at least 3% of a thermally stable titanium dioxide containing not more than 18% silicon, calculated in terms of  $\text{SiO}_2$  on dry basis;
- b) a filler, preferably a silica filler; and, optionally
- c) a binder.

- 16 -

Preferably, the silica filler present in the catalyst is selected from the group includes both natural silica, namely, diatomaceous earth, optionally treated with an acid to remove impurities therefrom, and precipitated silicas or silica hydrogels, preferably free of sodium or potassium contamination.

In a preferred embodiment of the present invention, the filler is a purified diatomaceous earth, which is obtained after a treatment with an acid, preferably HCl or H<sub>2</sub>SO<sub>4</sub>, at a temperature in the range of between 20 and 100°C for about 0.5 to 5 hours. Subsequent to a washing stage, diatomaceous earth, substantially free of impurities such as sodium, potassium, calcium, magnesium, aluminum and acid residues, is obtained. Then this diatomaceous earth can be used as a filler according to the present invention.

The binder is optional according to the present invention, and is preferably selected from the group of colloidal solutions of silica or hydrogels of silicic acid.

It is known that the efficiency of a catalyst used in a chemical reaction is dependent on the rate of diffusion of the reaction reagents into the catalyst particulates and the rate of diffusion of the reaction products therefrom. The silica filler is important in determining the macroporous structure of the catalyst. The preferred filler according to the present invention is a diatomaceous earth having a porous structure consisting essentially of macropores, the diameter of which being about 1 micrometer. Precipitated silica with low surface area and without a developed microporous structure and silica hydrogel with similar properties can also be used as fillers.



- 17 -

The catalyst according to the present invention is preferably prepared as follows. The silicon-containing titanium dioxide (a dried or calcined material) or its silicon-containing titanium hydroxide precursor (in the form of a wet cake, suspension or a partially dried cake) is mixed with the filler material (in the form of a wet cake, partially dried cake, or a completely dried material), and, optionally with a binder. Generally the mixing is facilitated using suitable mechanical means for pastes mixing and malaxating. Optionally, appropriate amounts of water may be added into said mixture in order to obtain a homogeneous dough. The addition of water, however, may not be necessary in cases where the water content of the titanium hydroxide and the filler is sufficient to prepare a paste with the required properties. In some cases the paste has to be dried to a certain extent in the process of dough preparation.

The resulting mixture is shaped into extrudates, beads, tablets, honeycombs or into blocks with any desired shape. The shaped forms obtained above are dried at a temperature in the range of between 50°C-300°C, and are subsequently calcined at a temperature in the range of between 300°C-800°C.

The mixing of the active ingredient with the filler, and optionally, with the binder, yields a mixture which is highly homogeneous, and which may be easily shaped into desirable granules or blocks, having high hardness.

The addition of binder, preferably a sol of silicic acid promotes higher hardness of the granulated material.

- 18 -

Preferably, the sol is introduced into the mixture containing the active ingredient and the filler in an amount not higher than 20% by weight (calculated in terms of  $\text{SiO}_2$ ). The resulting wet granules may be kept in air for some time or may be dried immediately. The drying process can be conducted at a wide range of temperatures, such as between ambient temperature and  $300^\circ\text{C}$ , using different types of dryers. Generally, the wet granules are first dried at a temperature in the range between  $100^\circ\text{C}$ - $150^\circ\text{C}$ , to increase their hardness to a degree allowing their loading into a calcination kiln, at a temperature of about  $400^\circ\text{C}$  for about 1 to 10 hours. The temperature of calcination may be increased up to  $800^\circ\text{C}$ .

The catalyst prepared according to the present invention possesses high thermal and hydrothermal stability and improved mesoporous and macroporous structure. The catalyst is characterized by improved hardness, and because of the excellent properties of active ingredient, relatively small quantities thereof are required to impart the catalyst excellent activity, in comparison to catalysts known in the art.

The novel catalyst of the present invention can be used in various processes, and particularly in processes involving sulfur recovery and in chemical reactions involving sulfur-containing compounds, such as, for example, the reaction of hydrogen sulfide with sulfur dioxide (known as Claus reaction). The following reactions may also be catalyzed using said catalyst: hydrolysis of carbonyl sulfide and carbon disulfide, direct oxidation of hydrogen sulfide with air and tail gases treatment (for example "Sulfreen" process).

The catalyst according to the present may be used in other chemical reactions, in which titanium dioxide is commonly used: the oxidation of carbon monoxide, the reduction of nitrogen oxide with ammonia, the complete oxidation of organic compounds, etc.

All the above description and examples have been provided for the purpose of illustration, and are not intended to limit the invention in any way.

#### Examples.

Methods of analyses: The modified titanium dioxide and catalysts obtained were analyzed by the following tests for the dry samples as well as for samples calcined at a temperature between 250°C to 900°C:

- determination of the specific surface area, using the so called "1 point method" with Analyzer 4200 (Leeds and Northrup),

- specific surface area and specific adsorption pore volume, as determined with a Coulter Instrument SA 3100,

- macropore structure, as determined by generally accepted mercury intrusion method, and

- the respective chemical analyses, carried out using known tests.

Specific tests of catalytic properties are described in corresponding examples

- 20 -

### Preparation A

#### Preparation of a solution containing dissolved ammonium titanyl sulfate salt

An amount of 2 kg of solid ammonium titanyl sulfate salt containing about 20% of  $\text{TiO}_2$  and 27% water, was dissolved in 4 l of demineralized water at room temperature overnight, using a moderate stirring. The non-dissolved portion was separated by filtration. The resulted solution contained 80 g/l titanyl sulfate (calculated as  $\text{TiO}_2$ ) which corresponds to the formula of the respective double salt  $(\text{NH}_4)_2\text{TiO}(\text{SO}_4)_2$  and an amount of ammonium sulfate. The pH of this solution was of 0.8.

### Preparation B

#### Preparation of an acidic titanyl sulfate solution

An acidic titanyl sulfate solution, which is compositionally similar to a commercially available acid titanyl sulfate solution, known as "UNITi 992", produced by Kemira Pigments Inc., was prepared as follows:

An amount of 9.8 kg of a commercial titanium dioxide (hydrolysate) UNITi 908, having a loss on ignition of 19.6% by weight (at  $1000^\circ\text{C}$ ), was dissolved in an amount of 43.8 kg of boiling sulfuric acid having a concentration of 70% by weight. After cooling, an amount of 1 l of this solution was diluted with an equal volume of demineralized water. The resulted solution, having a concentration of 123 g/l  $\text{TiO}_2$ , was used in examples 3 to 5. The same solution, but with another concentration of titanium dioxide was used in examples 6 to 18 (see table 2).

- 21 -

Example 1Preparation of silicon-containing titanium dioxide

Starting material: the solution of ammonium titanyl Sulfate.

Silica sol: basic silica sol containing ammonium cations.

Preparation the precipitate of titanium hydroxide : An amount of 175 g of urea was added to 500 ml of the solution prepared according to preparation A, at room temperature and the resulting solution was heated and maintained at a temperature in the range of between 97-102°C for about 3 hours. The precipitated titanium hydroxide was separated from the mother liquor and washed with demineralized water.

Preparation the silicon-containing titanium dioxide: The resulting wet cake of titanium hydroxide was suspended in a basic silica sol, prepared from a commercial sodium silicate solution as known in the art, the pH being increased to about 8.5 by treating with an aqueous solution of ammonia.

In this process an amount of about 41 g of the basic sol was mixed with the titanium hydroxide cake, corresponding to a  $\text{SiO}_2$  :  $\text{TiO}_2$  weight ratio of about 0.03. The mixture was maintained at about 90°C for 30 minutes under moderate stirring. The residual quantity of silicon in solution was negligible. The wet cake of titanium hydroxide was converted into titanium dioxide, by drying first at 110°C for about 2 hours and further at about 250°C for half hour. The properties of the product obtained are given in Table .1

- 22 -

below, in comparison to a commercially available titanium dioxide.

### Example 2

#### Preparation of silicon-containing titanium dioxide

Starting material: the solution of ammonium titanyl sulfate.

Silica sol: basic silica sol containing ammonium cations.

The titanium dioxide was prepared as in Example 1, but the amount of the basic silica sol used corresponded to a weight ratio  $\text{SiO}_2:\text{TiO}_2$  to 0.05. The data on the specific surface areas of the prepared sample and the respective thermal stability, compared with a commercially available titanium dioxide, known as UNITi 908, are given in Table 1.

Table 1

| Product   | Specific surface area of initial titanium dioxide, $\text{m}^2/\text{g}$ | Weight ratio $\text{SiO}_2:\text{TiO}_2$ | Specific surface area of samples treated with basic silica sol, $\text{m}^2/\text{g}$ |  |       |
|-----------|--|--|---|--|-------|
|           |  |  | Dried Sample  | ! After calcination ! for 3 hours, at ! a temperature of 500°C | 700°C |
| Example 1 | 392  | 0.03                                     | 436   | 207  | 113   |
| Example 2 | 399  | 0.05                                     | 448   | 283  | 144   |
| UNITi 908 | 328  |  |   | 93   | 24    |

- 23 -

Examples 3 to 5Preparation of silicon-containing titanium dioxide

Starting material: the acidic titanyl sulfate solution.

Silica sol: basic silica sol stabilized with  
different cations.

Preparation of a precipitate of titanium hydroxide: 1 liter of the acidic titanyl sulfate solution obtained by preparation B was gradually neutralized with 481 grams of an aqueous solution of ammonia, containing about 25% by weight of ammonia. The temperature of the starting solution was 22°C, but, as the heat of the neutralization releases, it may be increased to about 35-55°C. To the above solution, an amount of 780 ml of demineralized water was added and the resulting solution had a pH of 0.90. To the above mentioned solution, an amount of 409 g of urea was added and then heated to 98°C and maintained at this level for about two and half hours (see Table 2). The precipitated titanium hydroxide was separated from the mother liquor and washed with demineralized water. The resulting wet cake was divided into three portions, used in the Examples 3, 4 and 5. Each wet cake sample was diluted with demineralized water, obtaining a suspension which had a concentration of 10% (calculated as  $\text{TiO}_2$ ).

Preparation of silicon-containing titanium dioxide: three basic silica sol was prepared by a method known in the art, using different cations for the sol stabilization; in Example 3: sodium, in Example 4: potassium and in Example 5: ammonium. In each Example, the amount of basic sol used, calculated as % of  $\text{SiO}_2$  to  $\text{TiO}_2$  was 10% (by weight).

- 24 -

The three different basic silica sols were mixed separately with the above mentioned three samples of suspension and the resulting mixtures were heated to about 90°C and maintained at this temperature for about 1 hour. In each case, substantially all the quantities of silica were consumed by the titanium hydroxide. The resulted precipitates were separated from the liquid phase by filtration and converted into titanium dioxides by a thermal treatment at four different temperatures: 110°C, 500°C, 700°C and 900°C. The conditions of preparation are given in table 2.

**Table 2**

| Ex. No. | Concentration of titanium hydroxide in the suspension (as % TiO <sub>2</sub> ) | Concentration of silica sol (as g/l SiO <sub>2</sub> ) | Cationic Form of silica sol  | Quantity of silica sol (in terms of % SiO <sub>2</sub> in TiO <sub>2</sub> ) |                                |
|---------|--|--|------------------------------|--|--------------------------------|
|         |  |  |                              | introduced   | consumed by Titanium hydroxide |
| 3       | 10   | 3.0  | Na <sup>+</sup>              | 10.0   | 9.9                            |
| 4       | 10   | 3.0  | K <sup>+</sup>               | 10.0   | 9.9                            |
| 5       | 10   | 2.9  | NH <sub>4</sub> <sup>+</sup> | 10.0   | 9.9                            |

In table 3, values of specific surface area are detailed for titanium dioxide prepared according to examples 3 to 5, before and after the reaction with silica sol.

**Table 3**

| Ex. No. | Specific surface Area of titanium dioxide obtained without the treatment with silica sol (precipitate dried at 110°C) | Specific surface area of titanium dioxide obtained after the treatment with basic silica sol, m <sup>2</sup> /g |   |     |     |     |
|---------|---|---|---|-----|-----|-----|
|         |   | Dried (110°C)   | ! After calcination ! for 3 hours, at ! a temperature (°C) of |     |     |     |
|         |   |   | 500   | 700 | 800 | 900 |
| 3       | 416   | 442   |   |     | 141 | 65  |
| 4       | 416   | 434   |   |     | 139 | 65  |
| 5       | 416   | 453   | 327   | 277 | 164 | 110 |



- 25 -

It is apparent that silica sol stabilized with a variety of cations can be used in accordance with the present invention, most preferred being silica sol stabilized with ammonium cation.

#### Examples 6 to 17

##### Preparation of silicon-containing titanium dioxide

Starting material: the acidic titanyl sulfate solution.

Silica sol: basic silica sol stabilized with ammonium cations.

In these Examples, an acidic titanyl sulfate solution, according to preparation B, was used as a starting material.

Preparation of a precipitate of titanium hydroxide: The exact conditions for each example (dilution of the starting solution, pH adjustment, amount of urea added and duration of heating of the solution to generate the ammonia) are detailed in table 4.

Table 4

| Ex. No. | Concentration of TiO <sub>2</sub> in the starting solution | pH before the addition of urea | Weight ratio Urea:TiO <sub>2</sub> | Duration of heating (hours) |
|---------|--|--------------------------------|------------------------------------|-----------------------------|
| 6       | 125  | 1.10                           | 3.6                                | 2.5                         |
| 6A      | 125  | 1.10                           | 3.6                                | 2.5                         |
| 7       | 128  | 0.80                           | 2.0                                | 2.5                         |
| 8       | 128  | 1.67                           | 2.0                                | 5.5                         |
| 9       | 128  | 1.67                           | 2.0                                | 5.5                         |
| 10      | 123  | 0.8                            | 2.8                                | 2.3                         |
| 11      | 70   | 0.97                           | 2.9                                | 3.5                         |
| 12      | 123  | 0.84                           | 3.6                                | 4.0                         |
| 13      | 120  | 0.97                           | 2.1                                | 3.5                         |
| 14      | 126  | 0.02                           | 10.3                               | 3.0                         |
| 15      | 122  | 0.92                           | 3.6                                | 2.3                         |
| 16      | 126  | 1.20                           | 1.5                                | 2.5                         |
| 17      | 91   | 0.69                           | 2.6                                | 2.2                         |

\* In Examples 6 and 6A the solution was maintained at 50°C for 5 hours and 30 minutes, before urea addition;

\*\* In Example 15 the solution was maintained at 55°C for 8 hours after urea addition;

\*\*\* In Example 17, the acid titanyl sulfate solution of preparation B was first neutralized with calcium carbonate reaching a pH of 0.09, then the formed calcium sulfate was filtered out. The final neutralization of the solution was carried out with ammonium bicarbonate, reaching a pH of 0.69 as shown in table 4.

Preparation of silicon-containing titanium dioxide: The exact conditions of treating the precipitate of titanium hydroxide (in the form of a suspension or a wet cake) with silica sol, for each example, are indicated in table 5.

- 27 -

Table 5

| Ex. No. | Concentration of titanium hydroxide in the suspension (as % $\text{TiO}_2$ ) | Concentration of silica sol (as g/l $\text{SiO}_2$ ) | Cationic Form of silica sol | Quantity of silica sol (in terms of % $\text{SiO}_2$ in $\text{TiO}_2$ ) |                                |
|---------|--|--|-----------------------------|--|--------------------------------|
|         |  |  |                             | introduced   | consumed by Titanium hydroxide |
| 6       | 10   | 3.2  | $\text{NH}_4^+$             | 7.0  | 6.9                            |
| 6A      | 10   | 3.3  | $\text{NH}_4^+$             | 15.0   | 13.8                           |
| 7       | 10   | 3.0  | $\text{NH}_4^+$             | 2.0  | 2.0                            |
| 8       | 10   | 3.4  | $\text{NH}_4^+$             | 3.0  | 3.0                            |
| 9       | 10   | 3.4  | $\text{NH}_4^+$             | 7.0  | 6.0                            |
| 10      | Wet cake   | 3.2  | $\text{NH}_4^+$             | 30.0   | 15.3                           |
| 11      | 12   | 3.3  | $\text{NH}_4^+$             | 10.0   | 10.7                           |
| 12      | Wet cake   | 20.6   | $\text{NH}_4^+$             | 16.5   | 13.4                           |
| 13      | 15   | 11.6   | $\text{NH}_4^+$             | 5.0  | 5.0                            |

The properties of the titanium dioxides, also in comparison to titanium dioxides known in the art, are given in the following tables.

**Table 6**

| Ex. No.   | Specific surface Area of titanium dioxide obtained without the treatment with silica sol (precipitate dried at 110°C) | Specific surface area of titanium dioxide obtained after the treatment with basic silica sol, m <sup>2</sup> /g |  |     |     |
|-----------|---|---|--|-----|-----|
|           |   | Dried (110°C)   | ! After calcination ! for 3 hours, at ! a temperature (°C) of ! 500      700      800      900 |     |     |
| 6         | 424   | 470   | 285  | 170 | 116 |
| 6A        | 416   | 478   | 357  | 269 | 203 |
| 7         | 393   | 393   |  | 53  | 28  |
| 8         | 390   | 448   |  | 111 | 72  |
| 9         | 390   | 450   |  | 170 | 119 |
| 10        | 360   |   | 312  |     | 228 |
| 11        | 403   | 429   |  |     | 142 |
| 12        | 406   | 430   | 367  | 269 |     |
| 13        | 400   | 435   | 238  | 141 |     |
| 14        | 434   |   |  |     |     |
| 15        | 460   | 490   |  |     |     |
| 16        | 416   |   |  |     |     |
| 17        | 402   |   |  |     |     |
| UNITi 908 |   | 328   | 93   | 24  |     |

**Table 7**

Hydrothermal stability of the modified titanium dioxides in comparison with commercially available materials.

| Example No.                   | Specific surface area (m <sup>2</sup> /g), after steaming <sup>x</sup> during 5 hours at 400°C |
|-------------------------------|--|
| 6                             | 173  |
| 6A                            | 320  |
| 21                            | 132  |
| Commercial TiO <sub>2</sub> : |  |
| UNITi 908                     | 94   |
| S-150                         | 84   |

- 29 -

Note: \* the steaming stream contained 90% by volume water vapors, and 10% by volume air.

Table 8Sulfur content of modified titanium dioxides

Sulfur content, (% by weight)

| Example No.                 | Calculated as sulfur | Calculated as (SO <sub>4</sub> <sup>2-</sup> ) |
|-----------------------------|----------------------|--|
| 1                           | 0.04                 | 0.12   |
| 5                           | 0.24                 | 0.72   |
| 10                          | 0.10                 | 0.30   |
| 22                          | 0.07                 | 0.21   |
| Commercial titanium dioxide | 0.3-1.0              | 0.9-3.0  |

**Table 9**

Specific surface area distribution on pore diameters of modified titanium dioxides in comparison with known ones

| Example   | Total specific surface area |   | Specific surface area formed by pores with a diameter greater than: |   |                   |   |                   |   |
|---|-----------------------------|---|---|---|-------------------|---|-------------------|---|
|   | m <sup>2</sup> /g           | ln % of analogous value for a commercial sample S-140 | m <sup>2</sup> /g   | ln % of analogous value for a commercial sample S-140 | m <sup>2</sup> /g | ln % of analogous value for a commercial sample S-140 | m <sup>2</sup> /g | ln % of analogous value for a commercial sample S-140 |
| <u>Example 6</u>  |                             |   |   |   |                   |   |                   |   |
| TiO <sub>2</sub> before treating with basic silica sol.                   | 424                         | 129   | 180   | 253   | 334               | 380   | 352               | 352   |
| TiO <sub>2</sub> treated with basic silica sol as described in Example 6  | 470                         | 143   | 251   | 375   | 352               | 400   | 371               | 371   |
| <u>Example 6 A</u>  |                             |   |   |   |                   |   |                   |   |
| TiO <sub>2</sub> treated with basic silica sol as described in Example 6A | 476                         | 145   | 319   | 476   | 367               | 417   | 378               | 393   |
| <u>Example 15</u>   |                             |   |   |   |                   |   |                   |   |
| TiO <sub>2</sub> before treating with basic silica sol                    | 490                         | 149   | 182   | 272   | 242               | 275   | 259               | 270   |
| Commercial TiO <sub>2</sub>   |                             |   |   |   |                   |   |                   |   |
| UNITi-908   | 328                         | 100   | 48  | 72  | 62                | 70  | 67                | 70  |
| Commercial TiO <sub>2</sub> S-140   | 329                         | 100   | 67  | 100   | 88                | 100   | 96                | 100   |

Note: all the data listed in this Table were measured with Coulter Instrument SA 3100.

Table 10

The adsorption pore volume distribution on pore diameters of modified titanium dioxide samples compared with known ones.

| Example .   | Adsorption pore volume formed by pores with diameter |                   |  |                   |  |                   |
|---|--|-------------------|--|-------------------|--|-------------------|
|   | less than 100 nm                                     |                   | greater than 4.1 nm                    |                   | greater than 3.5 nm                    |                   |
|   | cc/g   | In % of analogous | cc/g                                   | In % of analogous | cc/g                                   | In % of analogous |
|   | value for commer-<br>cial sample S-140               |                   | value for commer-<br>cial sample S-140 |                   | value for commer-<br>cial sample S-140 |                   |
| <u>Example 6</u>  |  |                   |  |                   |  |                   |
| TiO2 before the<br>treatment with<br>basic silica sol                   | 0.47   | 147               | 0.23                                   | 110               | 0.41                                   | 178               |
| TiO2 treated<br>with basic silica<br>sol as described<br>in Example 6   | 0.52   | 163               | 0.31                                   | 148               | 0.41                                   | 178               |
| <u>Example 6 A</u>  |  |                   |  |                   |  |                   |
| TiO2 treated with<br>basic silica sol<br>as described in<br>Example 6 A | 0.63   | 180               | 0.49                                   | 233               | 0.54                                   | 235               |
| <u>Example 15</u>   |  |                   |  |                   |  |                   |
| TiO2 before the<br>treatment with<br>basic silica sol                   | 0.56   | 160               | 0.36                                   | 171               | 0.40                                   | 174               |
| Commercial TiO2<br>UNITI- 908   | 0.32   | 91                | 0.20                                   | 105               | 0.22                                   | 96                |
| Commercial TiO2<br>S-140  | 0.35   | 100               | 0.21                                   | 100               | 0.23                                   | 100               |

Note: all the data listed in this Table were measured with Coulter Instrument SA 3100.

- 32 -

Table 11

Comparison of thermal stability of the modified titanium dioxide prepared according to the present invention and a mixed titania-silica oxide as described in US 4,221,768

| Samples prepared according to the present invention and calcined at 500°C for 3 hours |   |   | Samples as described in US Patent 4,221,768 (calcined at 500°C for 3 hours) |   |   |
|---|---|---|---|---|---|
| Example No.   | TiO <sub>2</sub> content of the sample (%) by weight) | Specific surface area (m <sup>2</sup> /g) | Example No.   | TiO <sub>2</sub> content of the sample (%) by weight) | Specific surface area (m <sup>2</sup> /g) |
| 12  | 86  | 367                                       | 1   | 84  | 220                                       |
|   |   |   | 4   | 84  | 280                                       |
| 5   | 90  | 327                                       | 6   | 91  | 230                                       |

Table 12

Specific surface areas of calcined titanium dioxide according to the present invention compared with those described in European Patent Applications Nos. 0 576 120 and 0 311 515.

Specific surface area of calcined samples  
(m<sup>2</sup>/g)

| temperature of calcination | duration of calcination | The present invention |            | EP 576120 | EP 311515 |
|----------------------------|-------------------------|-----------------------|------------|-----------|-----------|
|                            |                         | Example 6             | Example 10 | Example 1 | Example Q |
| 575                        | 1                       | 229                   | 360        |           | 93        |
| 575                        | 7                       | 210                   | 350        |           | 85        |
| 800                        | 3                       | 116                   | 228        | 65.6      |           |



TABLE 13:

Comparison between structural indicators of calcined samples prepared according to the present invention and those described in the literature.

| Prepared according to the present invention |  |                      |   |  | Described in literature   |                      |   |  |             |  |  |
|---|--|----------------------|---|--|---|----------------------|---|--|-------------|--|--|
| Example                                     | Quantity of<br>silicon<br>introduced<br>in the titania's<br>structure<br>calculated<br>as SiO2,% | Calcining conditions |   | Specific<br>surface<br>area<br>(m <sup>2</sup> /g) | Quantity<br>of silica<br>in titania<br>/ silica<br>mixed<br>oxides<br>(%) | Calcining conditions |   | Specific<br>surface<br>area<br>(m <sup>2</sup> /g) | References  |  |  |
|   | Temperature<br>°C  | Duration<br>hours    |   |  | Temperature<br>°C   | Duration<br>hours    |   |  |             |  |  |
|   |  |                      |   |  |   |                      |   |  |             |  |  |
|   |  |                      |   |  |   |                      |   |  |             |  |  |
| 5   | 9.9  | 700                  | 3 | 277  | 20.0  | 600                  |   | 85   | Applied     |  |  |
| 6   | 6.9  | 700                  | 3 | 170  |   |                      |   |  | Catalysis   |  |  |
| 8   | 3.0  | 700                  | 3 | 111  |   |                      |   |  | A: General  |  |  |
| 5   | 9.9  | 800                  | 3 | 164  |   |                      |   |  | 139(1996)   |  |  |
| 10  | 15.3   | 900                  | 3 | 146  |   |                      |   |  | 175-187     |  |  |
| 6   | 6.9  | 500                  | 3 | 285  | 25.0  | 500                  | 2 | 213  | Journal     |  |  |
| 6 A   | 13.8   | 500                  | 3 | 357  |   |                      |   |  | of          |  |  |
| 12  | 14.0   | 500                  | 3 | 367  |   |                      |   |  | catalysis   |  |  |
| 21  | 7.0  | 500                  | 3 | 234  |   |                      |   |  | 105,511-520 |  |  |
| 22  | 15.0   | 500                  | 3 | 227  |   |                      |   |  | (1987)      |  |  |

It is apparent from the above tables that the novel silicon-containing titanium dioxides are significantly superior, concerning the thermal and hydrothermal stability, over known titania and known titania-silica mixed oxides.

#### Example 18

Samples of titanium dioxide of Example 6 and of commercially available titanium dioxide (UNITi 908) were calcined at 950°C for one hour. Figures 1 and 2 depict the diffraction

- 34 -

pattern of said calcined samples, respectively. It is apparent from Figure 1 that the thermally stable titanium dioxide of Example 6 maintained the favorable crystalline structure of the Anatase form after the calcination, while the crystalline structure of commercial material (UNITi 908) was partially converted into the catalytically unfavorable Rutile form (Figure 2).

#### Example 19

The sample prepared in Example 12 was investigated by the EDAX method, to determine the local composition of the titanium dioxide at two different points and the composition of the bulk. The results are detailed in the following table 14:

Table 14

|         | TiO <sub>2</sub> | SiO <sub>2</sub> | CaO    |
|---------|------------------|------------------|--------|
| Point 1 | 87.5             | 12.3             | 0.2    |
| Point 2 | 87.7             | 12.3             | absent |
| Bulk    | 87.8             | 12.1             | 0.1    |

It is apparent from the above table, that, despite very slight variations from one point to another, titanium and silicon are present in each point of the novel titanium dioxide. No separate phases of TiO<sub>2</sub> or SiO<sub>2</sub> exist. The calcium observed is merely a casual impurity in the sample.

- 35 -

EXAMPLES 20-22.Preparation of silicon-containing titanium dioxidesStarting material: commercially available titanium dioxideSilica sol: basic silica sol stabilized with ammonium cations.

In these Examples, the process according to the present invention was carried out using commercially available titanium dioxides as the starting material. In Examples 20 and 21, titanium hydrolysates (S-140 and S-150) as produced by KEMIRA PIGMENT OY (Finland) were used. In Example 22, a hydrolysate (UNITi 908) produced by KEMIRA PIGMENT (U.S.A.) was used. The preparation data is summarized in the following table 15:

Table 15Commercial titanium dioxides modified with silica sol.

| Example No. | The sample of the TiO <sub>2</sub> used | Quantity of used TiO <sub>2</sub> (grams) | Concentration of silica sol as % SiO <sub>2</sub> in sol | Suspension or wet cake were treated | Quantity of silica sol, as % SiO <sub>2</sub> calculated on TiO <sub>2</sub> |                              |
|-------------|---|---|--|-------------------------------------|--|------------------------------|
|             |   |   |  |                                     | Introduced in the suspension or in the cake                                  | taken up by TiO <sub>2</sub> |
| 20          | S-140                                   | 200                                       | 3.1  | suspension                          | 7  |                              |
| 20          | S-140                                   | 200                                       | 3.1  | suspension                          | 10   |                              |
| 20          | S-140                                   | 200                                       | 3.1  | suspension                          | 14   |                              |
| 21          | S-150                                   | 200                                       | 3.3  | suspension                          | 7  |                              |
| 21          | S-150                                   | 200                                       | 3.3  | suspension                          | 10   |                              |
| 22          | UNITi 908                               | 10  | 20.6   | wet cake                            | 15   | 13                           |

The properties of the titanium dioxides of the present invention, prepared by using commercially available titanium hydroxides/dioxides as the starting material, are given in table 16:

**Table 16**

Specific surface areas of commercial titanium dioxides modified with ammonium silica sols.

| Ex. No. | Quantity of silica Sol as % SiO <sub>2</sub> in TiO <sub>2</sub> | Specific surface area of titanium dioxide obtained after the treatment with basic silica sol, m <sup>2</sup> /g |   |     |     |    |
|---------|--|---|---|-----|-----|----|
|         |  | Dried (110°C)   | ! After calcination ! for 3 hours, at ! A temperature of ! 500                      700                      800                      900 |     |     |    |
| 20      | none   | 329*  | 16  |     |     |    |
| 20      | 7  |   | 101   | 58  |     |    |
| 20      | 10   |   | 119   |     |     |    |
| 20      | 14   |   | 191   | 143 | 94  |    |
| 21      | 7  | 290   | 234   | 102 | 90  |    |
| 21      | 10   |   | 126   |     |     |    |
| 22      | 15   |   | 227   | 210 | 116 | 80 |
| 22      | none   | 328   | 93  | 24  |     |    |

\*measured by a Coulter Instrument

The beneficial effects of the method according to the present invention, are evident from the Tables 6, 7, 8.

### Example 23

A samples of titanium dioxide of Examples 22 was calcined at 950oC for one hour. Figures 3 depict the X-ray diffraction pattern of said calcined samples. It is apparent from from comparison of Figures 2 and 3 that the thermally stable

- 37 -

titanium dioxide of Example 22 maintained the favorable crystalline structure of the Anatase form after the calcination, while the crystalline structure of commercial titanium dioxide was partially converted into Rutile form.

#### Example 24 (comparative)

In this example, an acidic silica sol was introduced directly into a titanyl sulfate solution of preparation B in an amount corresponding to 10% as  $\text{SiO}_2$  (calculated on the basis of the  $\text{TiO}_2$  content of the solution, present as titanyl sulfate). The titanyl sulfate solution was first diluted to a concentration of 70 g/l of  $\text{TiO}_2$ . The pH was adjusted to 0.93 using ammonia, The resulting solution was heated for 2.6 hours (urea:  $\text{TiO}_2$  ratio being 3.0), and the precipitation of titanium hydroxide took place in the presence of silica sol.

The precipitate was dried at 110C, and had a specific surface area of 365  $\text{m}^2/\text{g}$ . After calcination of 3 hours at 500°C and 700°C, the surface area decreased to 234 and 115  $\text{m}^2/\text{g}$ , respectively.

#### Example 25

In this example, acidic and basic silica sols were used and their modifying effects were compared. The criterion of effectiveness was the decrease in the specific surface area of the titanium dioxides as prepared in Examples 13 and 16. In all these experiments corresponding titanium hydroxides were introduced into silica sols having a concentration of 3% calculated as  $\text{SiO}_2$ . In one experiment it was an acid sol and in another one, it was a basic sol stabilized with an ammonium cation. As can be noticed from Table 17, both the

- 38 -

acid and the basic sols produce the stabilizing effect, but the basic sol provides a higher stabilizing effect.

**Table 17**

Comparison of modificatory effects of acid and basic silica sols.

| Example No. | Specific surface area of original TiO <sub>2</sub> , (m <sup>2</sup> /g) | Type of silica sol | Quantity of silica sol, as % SiO <sub>2</sub> in TiO <sub>2</sub> | Specific surface area (m <sup>2</sup> /g), after calcination for 3 hr at a temperature of |       |
|-------------|--|--------------------|---|---|-------|
|             |  |                    |   | 500°C   | 700°C |
| 13          | 400  | acidic             | 8   |   | 107   |
| 14          | 400  | basic              | 5   | 242   | 145   |
| 15          | 416  | acidic             | 4   | 155   | 62    |
| 16          | 416  | basic              | 4   | 230   | 123   |
| 17          | 416  | without            |   | 111   | 8     |

**Example 26**

In this Example the effectiveness of the modified titanium dioxide as an active component of Claus catalyst, is demonstrated.

The modified titanium dioxide as obtained in Example 1, was mixed with powdery silica N60 (produced by PPG) and an acid silica sol. The powdery silica was used as an inert filler and the silica sol was used as a binder component. The composition of this mixture, in weight percentage was as follows:

|  |            |
|--|------------|
| Modified titanium dioxide                    | 24.9%      |
| Powdery silica                               | 64.6%, and |
| Silica sol (calculated as SiO <sub>2</sub> ) | 10.5%      |

The mixture was granulated into extrudates with a diameter of 3.6 mm, dried at 110°C for two hours and then calcined at 400°C for three hours. The results with this catalyst tested in a bench scale pilot plant, using the known conditions as used in the Claus process were as follows:

|                                    |       |
|------------------------------------|-------|
| $\text{H}_2\text{S} + \text{SO}_2$ | 100 * |
| $\text{COS} + \text{H}_2\text{O}$  | 100   |
| $\text{CS}_2 + \text{H}_2\text{O}$ | 98.   |

(\*expressed the activity as shown by the conversion related to the equilibrium).

#### Example 27

This Example shows that the modified titanium dioxide can be used also as a carrier for catalysts which is effective in the oxidation of organic compounds in a gas phase.

Two samples were prepared and tested in a laboratory unit for the catalytic oxidation of propane (3 mol.%) in air at 400°C, In the two cases titanium dioxide was doped with vanadium oxide.

The compositions of the catalysts and the results of the respective tests are given in Table 18. As can be noticed the titanium dioxide as prepared by the present invention, is useful as a catalyst carrier for organic impurities in air oxidation.

Table 18Catalytic oxidation of propane in air at 400°C.

| Number of samples<br>from which titanium<br>dioxide was taken | Quantity of vanadia<br>introduced into TiO <sub>2</sub><br>(% by weight) | Quantity of doped<br>TiO <sub>2</sub> in catalyst<br>(% by weight) | Quantity of siliceous<br>filler and binder in<br>catalyst (% by weight) | Extent of<br>oxidation<br>(%) |
|---|--|--|---|-------------------------------|
| 5   | 3  |  |   | 100                           |
| 12  | 5  | 38   | 62  | 100                           |

Example 28

An experiment was carried out to show that the titanium dioxide prepared according to the present invention can be successfully used as a photocatalyst for the degradation of organic impurities in water by oxidation. The titanium hydroxide precipitated from the acid sulfate solution in the presence of urea and after washing was separated in the form of a wet cake containing 25% by weight TiO<sub>2</sub> before the treatment with basic silica sol (as in Example 7).

The procedure of the testing consists in the use of a suspension of 0.15 - 0.30 grams, calculated as TiO<sub>2</sub> placed in a bottle of 2 l. A quartz tube (internal diameter 1 cm and length 1 m) was used as a sun radiation reactor. Through this reactor and a bottle of water a stream containing 35 to 44 ppm of atrazine was pumped.



- 41 -

A comparative test with a commercial titanium dioxide (P-25, as produced by Degussa) was used for photodegradation of organic impurities in water. As can be noticed from Table 19, the titanium dioxide prepared according to the present invention can be useful also as a photocatalyst for this reaction.

Table 19

Photodegradation of atrazine in aqueous solutions

| Sample                                  | <u>Duration of degradation, hours</u> |          |          |          |
|---|---------------------------------------|----------|----------|----------|
|   | <u>0</u>                              | <u>1</u> | <u>2</u> | <u>3</u> |
| <u>Concentration of atrazine in ppm</u> |                                       |          |          |          |
| Titanium hydroxide                      |                                       |          |          |          |
| from Example 7                          | 35                                    | 28       | 23       | 17       |
| P-25 (Degussa)                          | 44                                    | 20       |          | 17       |

Example 29

This example demonstrates the preparation of a catalyst, possessing a high catalytic activity in the Claus process, with the modified titanium dioxide as an active component, powdery precipitated silica as a filler and silica sol as a binder material,

In this example the following starting materials were used:

- Modified titanium dioxide prepared according to Example 1.
- Powdery silica precipitated from a solution of sodium silicate with sulfuric acid.
- An acidic sol of silicic acid.

The modified titanium dioxide and powdery silica were dried at 105°C for 24 hours. After drying, the two materials had losses on ignition values (LOI) as shown in Table 20.

- 42 -

Acidic sol of silicic acid was prepared from sodium sol of silicic acid using a cation exchange resin C-100 produced by PUROLITE™.

An amount of 0.5 liter of sodium silica sol with a concentration of about 10% by weight, calculated on anhydrous silica dioxide, had been treated with the H-form of the above mentioned cation exchange resin thus obtaining an acid sol of silicic acid having a pH of about 3.0, and a SiO<sub>2</sub> content of 9.8% by weight.

The above materials were mixed in a laboratory mortar in the form of a paste, its composition calculated on dry basis, is given in Table 21.

The paste was passed through a laboratory extruder obtaining extrudates with a diameter of 3.0 mm. The extrudates were dried at 120°C for 3 hours in a laboratory dryer and then calcined at 400°C for 3 hours in a laboratory muffle. The structural properties of the catalyst obtained are given in Table 22. As can be noticed, the quantity of titanium dioxide present in 1 m<sup>3</sup> of catalyst bed, is only 140 Kg which is less than the quantity 777-900 kg present in a commercial catalyst (see Table 5). In order to test the catalytic activity of the above prepared extrudates, these were crushed and the fraction between 8 and 12 mesh was separated by sieving and then tested in a bench scale pilot plant using the conditions as for the Claus process. The results of the tests are given in Table 23.

- 43 -

Example 30.

This example demonstrates that the modified titanium dioxide can be calcined before its incorporation in the mixture with the other components of the catalyst.

The same modified titanium dioxide as in Example 29 was preliminary calcined at 350°C for 5 hours.

The paste mixture was prepared from this titanium dioxide, siliceous filler and a binder in a laboratory mortar (see Table 20); the composition of this paste, calculated on dry basis, is given in Table 20.

The paste had been formed into the same extrudates as in Example 29 in a laboratory extruder and then the extrudates were dried and calcined as in Example 29.

The structural properties of the prepared catalyst are given in Table 22.

The extrudates were crushed and the fraction with sizes of crumbs between 8 and 12 mesh, was tested in a bench scale pilot plant using the conditions as for Claus process. The results are given in Table 23.

Example 31 (comparative)

An experiment was carried out using a commercial titanium dioxide catalyst.

This catalyst was introduced in the same reactor as in Examples 29 and 30. The amount of the titanium dioxide used in this case, was substantially the same as in Example 29. It is apparent from Table 23 that the difference in carbon

- 44 -

disulfide conversion is equal to 10% which shows that the titanium dioxide present in the novel catalyst is more active than the same amount of titanium dioxide present in a commercial catalyst.

#### Examples 32- 34

In the preparation of the catalysts samples in a pilot plant, diatomaceous earth "CELITE FC" received from LOMPOS (USA) was used as an inert filler. The chemical composition of this material was as follows:

#### % by weight

|                                    |      |
|------------------------------------|------|
| SiO <sub>2</sub>                   | 85.8 |
| Al <sub>2</sub> O <sub>3</sub>     | 3.8  |
| Fe <sub>2</sub> O <sub>3</sub>     | 1.2  |
| CaO+MgO                            | 1.1  |
| Na <sub>2</sub> O+K <sub>2</sub> O | 1.1  |
| P <sub>2</sub> O <sub>5</sub>      | 0.2  |
| Loss on ignition                   | 3.6  |

The physical properties of this material were as follows:

|                                |     |
|--------------------------------|-----|
| Loose weight (g/liter)         | 120 |
| Oil absorption (% by weight)   | 128 |
| Water absorption (% by weight) | 280 |

As natural diatomaceous earth contains some undesirable impurities, such as sodium, potassium, iron, aluminum, it was preliminary purified by an acid treatment. For this purpose hydrochloric or sulfuric acid having a concentration of 15%-20% was used, the temperature during this treatment being between 90o-98o C for about 3 hours. The purified diatomaceous earth was filtered, washed with demineralized

- 45 -

water and used for the preparation of shapable dough in the form of wet cake or as a dried material. In some cases diatomaceous earth can be used as a filler without a preliminary purification.

In Examples 32, 33 and 34, the purified diatomaceous earth was used .

The titanium dioxide from Example 1 was used as an active component in Examples 32-34 together with a silica hydrogel, prepared by the following procedure, as a binder material:

Basic silica sol prepared in its sodium form, having an initial concentration of about 3% (calculated as  $\text{SiO}_2$ ) was evaporated to an extent that its concentration increased to 20-30% by weight. Then this sol was treated with a cation exchanger in order to eliminate the sodium and accordingly to decrease its pH to about 3.0. The resulted acidic sol was treated with an aqueous solution of ammonia until its pH increased up to 6-7 and then it was heated. During the heating coagulation of the sol into hydrogel took place and this hydrogel was used for the mixing with the other components.

The modified titanium dioxide in the form of a wet cake, a purified and dry diatomaceous earth and silica hydrogels were mixed in a double shaft mixer-sigma blade (produced by Sepor). After obtaining a homogeneous mixture, it was slightly dried in order to obtain a proper consistency suitable for extrusion. The extrudates having a diameter of 3.6 mm, were obtained with a piston extruder, dried at 120°C for about two hours and calcined at 450°C for 3 hours.

The losses on ignition are shown in Table 20, the compositions of the catalysts as prepared in a pilot plant

- 46 -

are given in Table 21 and the properties of the catalysts obtained are given in Table 24.

#### Examples 35-39

This group of Examples describes the preparation of the novel catalyst in the form of extrudates possessing a high hardness without any binder. In each case the catalyst consists of two components: the modified titanium dioxide and an inert filler, namely purified diatomaceous earth (as obtained in Examples 32-33). Losses on ignition for the components are shown in Table 20 and the compositions of the catalysts are given in Table 21.

In each case the active component was mixed with the inert filler and the resulted mixture was malaxated thus producing a shapable dough using a double shaft mixer, as described in Examples 32 to 34 and a piston extruder as used in a process of granulation. After drying at 120°C the extrudates were calcined in a muffle at a temperature of 450°C for 3 hours.

The following variations exist between the Examples 35 to 39:

In Example 35, diatomaceous earth was introduced as a wet cake after filtration, containing 35% of dry material. The paste was partially dried to 55.2% dry material, and then extruded using a piston extruder.

In other cases, diatomaceous earth was used in the form of a dried material (120°C) having a loss on ignition between 5% to 6% (see Table 20).

TABLE 20

Components used for catalysts preparation:

| Example No. | Modified titanium dioxide<br>(active component)<br>of example | Loss on<br>ignition,<br>weight % | Filler                     |                                  | Binder               |                                  | Loss on<br>ignition,<br>weight % |
|-------------|---|----------------------------------|----------------------------|----------------------------------|----------------------|----------------------------------|----------------------------------|
|             |   |                                  | Name                       | Loss on<br>ignition,<br>weight % | Name                 | Loss on<br>ignition,<br>weight % |                                  |
|             |   |                                  |                            |                                  |                      |                                  |                                  |
| 29          | 1   | 9.1                              | Powdery silica             | 7.8                              | Acidic silica sol    | 90.2                             |                                  |
| 30          | 2   | 3.0                              | "                          | 7.8                              | Acidic silica sol    | 90.2                             |                                  |
| 32          | 1   | 59.2                             | Diatoma-<br>ceous<br>earth | 5.0                              | Silica hydro-<br>gel | 70.3                             |                                  |
| 33          | 1   | 57.5                             | "                          | 4.0                              | Silica hydro-<br>gel | 74.5                             |                                  |
| 34          | 1   | 52.3                             | "                          | 4.0                              | Silica               | 79.5                             |                                  |

TABLE 20 (continued)

|    |   |              |   |     | hydro-<br>gel |
|----|---|--------------|---|-----|---------------|
| 35 | 10  | 63.7         | " | 6.5 | absent        |
| 36 | 12  | 62.5         | " | 8.0 | absent        |
| 37 | 9   | 70.0         | " | 5.0 | absent        |
| 38 | 6   | 73.0         | " | 4.0 | absent        |
| 39 | 6A  | 72.0         | " | 5.0 | absent        |
| 40 | 21 in amount of 37% and<br>22 in amount of 37%(by weight) | 63.0<br>59.0 | " | 5.0 | absent        |
| 41 | 21 in amount of 55% and<br>6 in amount of 15%             | 61.0         | " | 5.0 | absent        |



- 49 -

Table 21

Compositions of catalysts prepared in laboratory and in a pilot plant on the basis of precipitated modified titanium dioxides (% by weight calculated on dry basis)

EXAMPLES

|  | LABORATORY |      |      |      |      | PILOT PLANT |      |      |      |      |      |      |
|--|------------|------|------|------|------|-------------|------|------|------|------|------|------|
|  | 29         | 30   | 32   | 33   | 34   | 35          | 36   | 37   | 38   | 39   | 40   | 41   |
| Composition  |            |      |      |      |      |             |      |      |      |      |      |      |
| 1. TiO <sub>2</sub>                                      | 28.4       | 28.0 | 30.0 | 35.0 | 35.0 | 35.0        | 25.0 | 40.0 | 38.0 | 45.0 | 74.0 | 70.0 |
| 2. Siliceous component (calculated as SiO <sub>2</sub> ) | 60.2       | 61.4 | 55.0 | 55.0 | 55.0 | 65.0        | 75.0 | 60.0 | 62.0 | 55.0 | 26.0 | 30.0 |
| 3. Binder materials:                                     |            |      |      |      |      | none        | none | none | none | none | none | none |
| 3.1 Acidic silica sol                                    | 11.4       | 10.6 | none | none | none |             |      |      |      |      |      |      |
| 3.2 Silica hydrogel                                      | none       | none | 15.0 | 10.0 | 10.0 |             |      |      |      |      |      |      |

Table 22.

Structural properties of catalysts prepared in laboratory

| Example No. | Tamped bulk density, kg/m <sup>3</sup> | Specific surface area, m <sup>2</sup> /g | Composition of 1m <sup>3</sup> of a tamped catalyst bed, |                               |                  |
|-------------|--|--|--|-------------------------------|------------------|
|             |  |  | kg/m <sup>3</sup>  |                               |                  |
|             |  |  | Silica as a filler                                       | Silica as a binder (from sol) | Titanium dioxide |
| 29          | 490                                    | 134                                      | 294  | 55                            | 140              |
| 30          | 480                                    | 137                                      | 294  | 50                            | 134              |

Table 23.

Catalytic activity of novel catalysts, prepared in laboratory, in Claus process.

Extent of conversion in reactions

| Example No.   | H <sub>2</sub> S + SO <sub>2</sub> |                            | COS + H <sub>2</sub> O |               | CS <sub>2</sub> + H <sub>2</sub> O |               |
|---------------|------------------------------------|----------------------------|------------------------|---------------|------------------------------------|---------------|
|               | Initial Catalyst                   | Aged Catalyst <sup>2</sup> | Initial Catalyst       | Aged Catalyst | Initial Catalyst                   | Aged Catalyst |
| 29            | 93 <sup>1</sup>                    | 97 <sup>1</sup>            | 100                    | 100           | 96                                 | 90            |
| 30            | 97 <sup>1</sup>                    | 97 <sup>1</sup>            | 100                    | 100           | 97                                 | 91            |
| 31            | 94 <sup>1</sup>                    | -                          | -                      | -             | 86                                 | -             |
| (comparative) |                                    |                            |                        |               |                                    |               |

1 calculated as percentage of conversion at equilibrium state.

2 in all cases aging was carried out in a laboratory with a common hydrothermal treating and sulfating.

TABLE 24.

Properties of catalysts prepared in a pilot plant.

| Example No. | Hardness<br>(Crushing strength),<br>kg/extrudate | Specific surface area,<br>m <sup>2</sup> /g | Tamped bulk density,<br>kg/m <sup>3</sup> | Composition of a 1 m <sup>3</sup> of tamped catalyst bed, kg/m <sup>3</sup> |        |        |
|-------------|--|---|---|---|--------|--------|
|             |  |   |   | TiO <sub>2</sub>  | Filler | Binder |
| 32          | 20   | 165   | 635                                       | 191   | 349    | 95     |
| 33          | 17   | 175   | 634                                       | 222   | 222    | 63     |
| 34          | 12   | 179   | 567                                       | 198   | 312    | 57     |
| 35          | 20   | 174x  | 590                                       | 207   | 383    | absent |
| 36          | 12   | 166x  | 597                                       | 209   | 388    | absent |

TABLE 24. (continued)

|    |    |      |     |                  |     |        |
|----|----|------|-----|------------------|-----|--------|
| 37 | 9  | 144  | 545 | 191              | 354 | absent |
| 38 | 13 | -    | 617 | 234              | 383 | absent |
| 39 | 14 | 220x | 640 | 288              | 352 | absent |
| 40 | 9  | 164  | 800 | 592 <sup>1</sup> | 208 | absent |
| 41 | 11 | 187  | 700 | 490 <sup>2</sup> | 210 | absent |

Commercial

Claus

catalyst

based on

titanium

dioxides:

|     |   |      |      |     |   |   |
|-----|---|------|------|-----|---|---|
| "A" | 7 | 134x | 860  | 777 | - | - |
| "B" | 7 | 124x | 1000 | 900 | - | - |

Notes to table 24:

1. Mixture of stabilized commercial titanium dioxides (see Table 20).
2. Mixture of stabilized commercial titanium dioxide and precipitated titanium dioxide (see Table 20).
3. The sign x indicates that the values of specific surface area were determined with a Coulter instrument SA 3100. Figures without this sign were measured with an Analyser 4200 (Leeds and Northrup Instruments). In all the Tables the meaning of this sign is as above.

**TABLE 25**

Adsorption pore volume distribution on pore diameters for the novel catalyst in comparison with the commercial one

| Example No.                   | <u>Adsorption pore volume formed by pores with diameter:</u> |  |                     |  |                     |  |
|-------------------------------|--|--|---------------------|--|---------------------|--|
|                               | less than 100 nm   |  | greater than 4.1 nm |  | greater than 3.5 nm |  |
|                               | cc/g   | In % of the analogous values for the commercial catalyst "A" | cc/g                | In % of the analogous values for the commercial catalyst "A" | cc/g                | In % of the analogous values for the commercial catalyst "A" |
| 38                            | 0.33   | 127  | 0.31                | 129  | 0.32                | 123  |
| 39                            | 0.36   | 138  | 0.33                | 138  | 0.35                | 135  |
| Commercial Claus catalyst "A" | 0.26   | 100  | 0.24                | 100  | 0.26                | 100  |

Note: all the data listed in this table were measured with the Coulter Instrument SA 3100.

Table 26.

Macropore structure of catalysts prepared in a pilot plant  
in comparison with known ones.

| Example No.  | Pore volume formed by macropores with diameter<br>greater than indicated (cc/g) |                |        |        |
|--|---|----------------|--------|--------|
|  | 100 nm  | 200 nm         | 300 nm | 400 nm |
| Mixture of catalysts<br>from Examples 32, 33<br>and 34 | 0.38  | 0.30           | 0.20   | 0.05   |
| Mixture of catalysts<br>from Examples 35,<br>36 and 37 | 0.30  | 0.25           | 0.20   | 0.10   |
| Example 38   | 0.21  | 0.14           | 0.05   | 0.02   |
| Commercial Claus<br>catalysts:                         |   |                |        |        |
| A:   | 0.16  | 0.01           | -      | -      |
| B:   | 0.01  | less than 0.01 | -      | -      |
| C:   | 0.01  | less than 0.01 | -      | -      |

- 54 -

**TABLE 27:**

Thermal stability of catalysts prepared in a pilot plant in comparison with known Claus catalysts.

| Specific<br>Example No.                                      | surface area<br>of starting<br>catalyst, m <sup>2</sup> /g | Specific surface area of the catalyst calcined<br>for 3 hours at indicated temperatures, m <sup>2</sup> /g |       |       |       |
|--|--|--|-------|-------|-------|
|  |  | 500°C  | 700°C | 800°C | 900°C |
| 35   | 174x   |  |       | 89    | 58    |
| 38   | 175  |  | 121   | 109   |       |
| 39   | 220x   | 214  | 146   | 122   |       |
| 40   | 180x   | 164  | 118   | 79    |       |
| Commercial Claus<br>catalysts based<br>on TiO <sub>2</sub> : |  |  |       |       |       |
| A  | 134x   |  | 28    | 4     |       |
| B  | 110  | 103  | 43    | 22    | 8     |
| C  | 200  | 112  | 46    | 28    | 17    |

- 55 -

TABLE 28

Hydrothermal stability of the novel catalyst in comparison with known ones.

Conditions of the hydrothermal treatment:

-temperature: 500°C,

-treating agent: water vapor,

-duration: 5 hours:

Specific surface area (m<sup>2</sup>/g) of steamed catalyst, calculated:

| Example No. | per 1 gram | per 1 cc of tamped layer of a catalyst bed |
|-------------|------------|--|
|-------------|------------|--|

|    |     |    |
|----|-----|----|
| 38 | 120 | 74 |
|----|-----|----|

|    |     |    |
|----|-----|----|
| 39 | 135 | 86 |
|----|-----|----|

|    |     |    |
|----|-----|----|
| 40 | 113 | 90 |
|----|-----|----|

Commercial  
catalyst "A"

|                           |    |    |
|---------------------------|----|----|
| based on TiO <sub>2</sub> | 66 | 57 |
|---------------------------|----|----|

Commercial  
catalyst "B"

|                           |    |    |
|---------------------------|----|----|
| based on TiO <sub>2</sub> | 59 | 59 |
|---------------------------|----|----|

**TABLE 29.**Catalytic activity of catalysts prepared in a pilot plant

| Number of test | Catalytic process | Type of installation used for testing | Catalysts from Examples      | Extent of conversion in the reactions |                                      |
|----------------|-------------------|---------------------------------------|------------------------------|---------------------------------------|--------------------------------------|
|                |                   |                                       |                              | $\text{H}_2\text{S}+\text{SO}_2$      | $\text{COS/CS}_2+\text{H}_2\text{O}$ |
| 1              | Claus process     | Bench-scale pilot plant               | 35                           | 89                                    | 92                                   |
| 2              | Sulfreen process  | Big pilot                             | Mixture of Examples 32,33,34 |                                       |                                      |
|                | temperature 220°C |                                       |                              | 44                                    | 84                                   |
|                | temperature 250°C |                                       |                              | 38                                    | 90                                   |
| 3              | Sulfreen process  | Big pilot                             | Mixture of Examples 35,36,37 |                                       |                                      |
|                | temperature 220°C |                                       |                              | 44                                    | 84                                   |
|                | temperature 250°C |                                       |                              | 39                                    | 92                                   |
| 4              | Sulfreen process  | Big pilot                             | Commercial catalyst "C"      |                                       |                                      |
|                | temperature 220°C |                                       |                              | 43                                    | 81                                   |
|                | temperature 250°C |                                       |                              | 37                                    | 84                                   |

Note: in test 1 the extent of conversion in the reaction  $\text{H}_2\text{S}+\text{SO}_2$  is calculated as a percentage of conversion at equilibrium state, in the other tests real values of conversion for the reactions  $\text{H}_2\text{S}+\text{SO}_2$  and  $\text{COS/CS}_2+\text{H}_2\text{O}$ , both are listed.